Study on the Design Method Development and Impact Analysis of Crash Cushion Using Single Degree of Freedom

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Abstract

Crash cushion is a safety facility that can make a direction restore to the original lane or make it stop by absorbing the impact energy of vehicle. But development of crash cushion is defective because there's no rational and reality way of design. And also without an alternative plan, it rely on crash test hereby it suffers a great economic loss and wastes time.
This study proves the suitability of single degree of freedom considered passenger safety and performs design development of effective crash cushion to analyze behavior of collision of crash cushion. To verify the validness of the crash cushion design method, the researchers execute the crash test. A performance test brings satisfied result and judging from this, the design method of single degree of freedom is proved one of the best ways to design crash cushion

Key words : Crash Cushion, Design Method, Impact Analysis, Crash Test, Occupant Risk Index

1. Introduction

Crash cushion is a safety facility that can make a direction restore to the original lane or make it stop by absorbing the impact energy of vehicle. In Korea these days, many kinds of crash cushions have been positioned at several spots where vehicle collision is most likely to happen, like a bridge post, abutments of a bridge, a junction of a linking road exit, a tollgate, a tunnel and an underpass entrance.

According to the rules in KOREA, a crash cushion should pass standard vehicle crash test. For development of crash cushion, efficiency is completed the crash test. However, there is no reasonable method that considers passenger's safety and only depends on crash test without an alternative plan. Recently, numerical interpretation programs are used variously but modeling the structure of both the crash cushion and the car is complicated & difficult, resulting to high computational cost. Consequently the researchers are asked to develop a systematic design method.

For the design of facilities of the crash cushion considering passenger safety, this paper analyzes the behavior of collision of the crash cushion facility based on data of 34 crash tests. Hereby, the researchers conducted a basic survey that helps the development of the crash cushion. The suitability of single degree of freedom is verified through the comparison of passenger safety indexes. Crash test data(x-axis acceleration, y-axis acceleration, yaw angular velocity) are applicable to the passenger safety index, for the calculation of theoretical head impact velocity(THIV) and post-impact head deceleration(PHD). And other passenger safety index is calculated only x-axis acceleration.

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It is better to use the data of a vehicle crash test rather than using data of crash simulation on crash cushion in developing the safety crash cushion. On this study, crash test data of verified crash cushion CC1 level have been applied to single degree of freedom's design, and then have planned crash cushion CC2 level and CC3. Each level crash cushion used in this study is identical in character of critical structure and only has some differences in length considering validity transformational distance.

All of the crash cushion's main part is consist of steel in general. Physical property of the steel controls efficiently vehicle's impact load and is suitable improving for the facility's crash absorption performance. For developing of the crash cushion was ahead of steel structure analysis. On this study has developed crash cushion's design method stand on steel structure analysis.

This study proves the suitability of single degree of freedom considered passenger safety and performs design development of effective crash cushion to analyze behavior of collision of crash cushion.

2. Theoretical consideration on single degree of freedom

When a vehicle collides with the crash cushion, preserved part of the vehicle is assumed as a rigid body. After vehicle collision, impact energy was absorbed by the damaged part of crash cushion. If a constant spring which is resisting force about transformation of crash cushion is considered, impact of vehicle and crash cushion may be represented by a single degree of freedom as shown in figure 1 using a constant spring k , resisting force, which is generated by impact of crash cushion and mass of the vehicle, M .

The time of collision, the vehicle and crash cushion's character is nonlinear and the character is known easily as showing a graph that represents relationship between resisting force and displacement of the vehicle when collided.

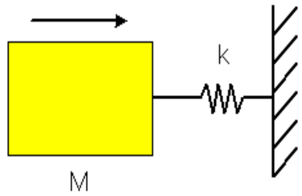


Figure 1. Crash cushion's model picture of single degree of freedom

The resisting force is found by multiplying mass of a vehicle and acceleration of a vehicle measured preserved part, a time record of displacement while crash is found by integrating measured acceleration twice. Suppose that mass of impact vehicle, M , acceleration measured the part of preserved vehicle, a , outside force like friction during collision, 0, then movement equation is organized.

$$f = Ma = 0 \tag{1}$$

When the outside force is 0, velocity of vehicle and displacement is equation (2), (3).

$$v = v_0 + \int_0^t adt \tag{2}$$

$$x = v_0 t + \int_0^{t'} \int_0^t adtdt' \tag{3}$$

This displacement x the represents displacement of a vehicle body and structure, velocity v_0 represents initial velocity, t, t' is the time on acceleration and velocity. Plus under ignorance of vehicle's displacement circumstances, displacement x sees displacement of structure. Upper process can show the graph of displacement and acceleration(x vs. a), the unit mass resisting force, applying to the result of simulation or crash test.

According to R. I. Emori study, complex oscillation the relationship between resisting force and displacement generating under the impact process of the vehicle and a rigid wall seems severe curves but becomes clear that it can be closely aligned at a fixed incline. Namely Emori analyzed the data of crash test, and then reached the result that a

unit mass of constant spring (k/M) has the constant value regardless of the impact velocity. That means that a rate of measured acceleration and displacement(a/x), is constant. The figure 2 sees the acceleration and displacement. (Emori, 1968)

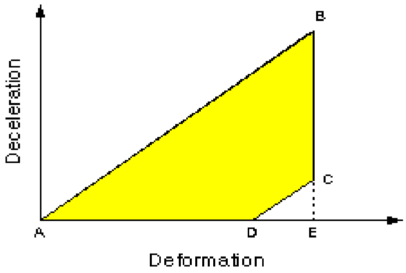


Figure 2. An ideal spring of single degree of freedom

Colored area in figure 2 shows movement energy of the unit mass of vehicle that is absorbed by nonlinear spring. When displacement of spring showed impact character of vehicle is x , resisting force f sees kx . Moreover, $f = kx = Ma$, then can be described by Newton's movement law. Since $k/M = a/x$ is affected, if a/x is constant, equally k/M is also constant. Because k/M is same as natural frequency of system, ω^2 , the movement equation of vehicle using single degree of freedom model can be written like this. (Go Man-ki, 2003)

$$\frac{a}{x} = \frac{-\ddot{x}}{x} = -\frac{k}{M} = -\omega^2 \qquad (4)$$

$$M\ddot{x} = kx = 0 \qquad (5)$$

At this point, let us supposes initial velocity , initial displacement 0.

$$\text{Displacement} : x = \frac{v_0}{\omega}\sin\omega t \quad (0 < \omega t < \frac{\pi}{2}),$$

$$x = 0 \quad (\frac{\pi}{2} \le \omega t) \qquad (6)$$

$$\text{Velocity} : \dot{x} = v_0 \cos\omega t \qquad (7)$$

$$\text{Acceleration} : \ddot{x} = -v_0\omega\sin\omega t \qquad (8)$$

Therefore, the maximum displacement and acceleration is represented a function of initial velocity .

$$|\ddot{x}_{max}| = \omega v_0 \qquad (9)$$

$$x_{max} = \frac{v_0}{\omega} \qquad (10)$$

If the character of vehicle-rigid wall impact can confirmed from the vehicle-crash cushion impact, design of reasonable crash cushion that considers passenger safety is quite possible. If rate of acceleration measured the vehicle-crash cushion impact and displacement coming from the acceleration(a/x) is confirmed in regardless of velocity, crash cushion's maximum displacement and the maximum acceleration can represent function of impact velocity. Vehicle transforming displacement that is compared with crash cushion's transforming displacement is much small, so it is neglected, and the maximum acceleration means X-axis maximum acceleration which is direction of impact.

3. Test condition and evaluation criteria of crash cushion

In the world, test condition and evaluation criteria of crash cushion are applied by considering each country's road condition and evaluation criteria is divided in USA NCHRP Report 350 and European Standard(CEN). Korean standard is the reorganized European standard and the condition of crash test sees in figure 3 and table 1.

According to KOREA guide, the standard of evaluation is divided in passenger protection capacity, behavior of crash cushion & behavior of vehicle after collision. There are two evaluation standards passenger collision velocity(THIV) and passenger acceleration(PHD). In case of THIV, test ①, ②, ③ should be below 44km/h , test ④, ⑤ below 33km/h and PHD should be below 20g.

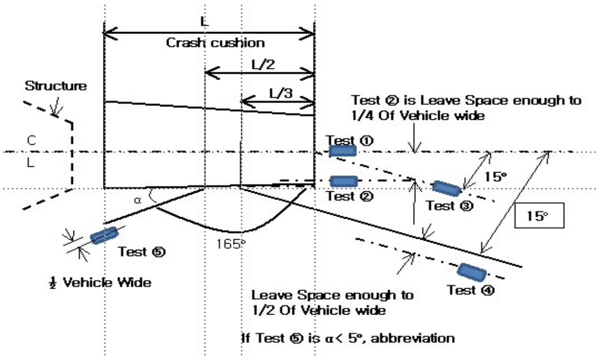


Figure 3. Collision spot and direction of collision vehicle

Table 1. Condition of collision test

Level	Collision velocity (Km/h)	total vehicle mass (Kg)	collision method
CC1	60	900 1,300	test ① test ②
CC2	80	900 1,300	test ①, ② test ①, ③, ④, ⑤
CC3	100	900 1,300	test ①, ② test ①, ③, ④, ⑤

4. Collision analysis of crash cushion for applying single degree of freedom

This study is analyzed crash test data that are executed 34 times in the Expressway & Transportation research Institute from Sep. 2005 to June. 2007. In here, this paper has excluded broadside collision(No ④, ⑤) data because passenger safety of broadside collision is shown very safe and broadside collision is not a test for passenger safety but for behavior of vehicle-crash cushion and scattering efficiency. Stage of crash cushion design considering passenger safety must be designed with an eye to head on collision rather than broadside collision.

Table 2 compares THIV and PHD that are result of head on collision and 15° broadside collision test based on identical crash cushion.

Test No ④`s THIV average is about Test No ① 40.2% and PHD shows relatively stable result 30.8%. Standard of PHD is provided under the 20g, Test ①, ④ but THIV Test ① should be under the 44km/h, Test ④ under the 33km/h. Therefore absolute comparison is unreasonable. Therefore, a THIV average of test No ① shows 87.8% of a valuation basis(44km/h) but even average of test No ④ shows 47.1% of a valuation basis(33km/h).

Therefore, crash cushion design considering passenger safety should focus on head on collision rather than broad side collision. 34 kinds of crash cushion used in the analysis presented difference in structural mechanism absorbing a collision load of a vehicle, an application level, a collision test method, collision vehicle weight, a size and material.

According to Korean guide, THIV is calculated with x-axis acceleration, y-axis acceleration and yaw angular velocity, PHD is calculated with x-axis acceleration, y-axis. Table 4, 5 compare calculation result by THIV and PHD.

Table 2. Comparison of occupant risk index head on collision & broad side collision

Test No.	Test Level	0.9ton, head on collision (Test No ①)		1.3ton 15°, side collision (Test No ④)	
		THIV (Under 44km/h)	PHD (Under 20g)	THIV (Under 33km/h)	PHD (Under 20g)
Test 1	CC1	31.0	14.1	16.2	10.1
Test 2	CC1	33.7	30.3	14.9	1.1
Test 3	CC1	43.7	18.3	14.0	1.4
Test 4	CC1	39.9	11.0	16.8	1.8
Test 5	CC1	38.0	18.5	12.4	5.1
Test 6	CC1	40.2	12.6	15.9	9.1
Test 7	CC2	43.8	13.0	18.5	7.7
Average		38.61	16.83	15.53	5.19

Table 3. Comparison of cc1 crash cushion's occupant risk index

Test No	condition	result	calculated all of X, Y, Yaw				Calculated of X-axis acceleration			
			THIV		PHD		THIV		PHD	
			Km/hr	sec	g's	sec	Km/hr	sec	g's	sec
No.01-CC1	①-0.9 F	Good	43.7100	0.1152	18.3284	0.1570	43.7086	0.1152	18.2601	0.1569
No.02-CC1	①-0.9 F	Good	41.6008	0.1169	16.0170	0.1574	41.4627	0.1169	15.9295	0.1574
No.03-CC1	①-0.9 F	Good	39.9431	0.1206	11.0450	0.1564	39.9409	0.1206	11.0449	0.1564
No.04-CC1	①-0.9 F	Good	35.4276	0.1227	18.5250	0.1561	35.4268	0.1227	18.5249	0.1561
No.05-CC1	①-0.9 F	Good	38.0454	0.1116	18.4745	0.1543	38.0292	0.1116	18.4556	0.1543
No.06-CC1	①-0.9 F	Good	40.1771	0.1186	12.6479	0.1358	40.1411	0.1186	12.5734	0.1356
No.07-CC1	①-0.9 F	NG	30.8741	0.1446	43.9931	0.1735	30.8711	0.1446	43.9431	0.1736
No.08-CC1	①-0.9 F	NG	42.1811	0.1147	24.2970	0.1335	42.1787	0.1147	24.2337	0.1335
No.09-CC1	①-0.9 F	NG	52.8988	0.0953	29.6503	0.0996	52.8546	0.0953	29.2760	0.0995
No.10-CC1	①-0.9 F	NG	57.2705	0.0994	18.9891	0.0994	57.2336	0.0994	18.8352	0.0994

Table 4. Comparison of cc2 crash cushion's occupant risk index

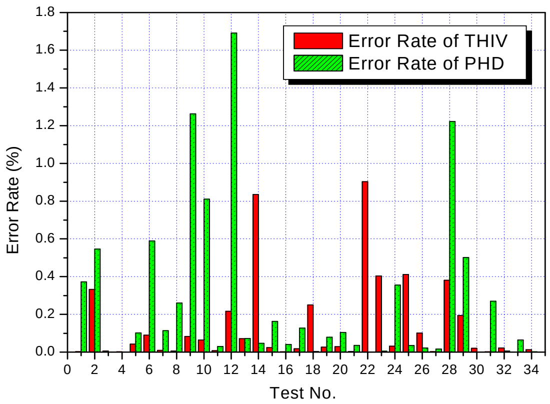
Test No	condition	result	Calculated all of X, Y, Yaw				Calculated of X-axis acceleration			
			THIV		PHD		THIV		PHD	
			Km/hr	sec	g's	sec	Km/hr	sec	g's	sec
No.11-CC2	①-0.9 F	Good	42.0251	0.0973	10.6033	0.2886	42.0218	0.0973	10.6001	0.2886
No.12-CC2	①-0.9 F	Good	42.4902	0.0938	9.6143	0.0981	42.3983	0.0938	9.4517	0.0979
No.13-CC2	①-0.9 F	Good	43.8156	0.1004	13.0085	0.1266	43.7844	0.1004	12.9991	0.1266
No.14-CC2	②-0.9 O	Good	38.8899	0.1016	16.2040	0.3013	38.5649	0.1016	16.1964	0.3013
No.15-CC2	②-0.9 O	Good	43.1883	0.1034	15.2749	0.1807	43.1780	0.1034	15.2500	0.1808
No.16-CC2	①-1.3 F	Good	37.4017	0.1034	16.0357	0.1153	37.4022	0.1034	16.0291	0.1153
No.17-CC2	①-1.3 F	Good	35.2950	0.1138	18.6516	0.2632	35.2886	0.1138	18.6278	0.2633
No.18-CC2	①-1.3 F	Good	33.9583	0.1167	17.0224	0.2990	33.8733	0.1167	17.0218	0.2990
No.19-CC2	①-1.3 F	Good	34.5902	0.1191	15.3571	0.2735	34.5809	0.1191	15.3450	0.2735
No.20-CC2	①-1.3 F	Good	33.8304	0.1192	13.4172	0.3114	33.8207	0.1192	13.4032	0.3096
No.21-CC2	①-1.3 F	Good	40.4505	0.1042	11.6040	0.1159	40.4490	0.1042	11.5998	0.1159
No.22-CC2	③-1.3 D	Good	36.1304	0.1136	15.0163	0.1788	35.8039	0.1136	15.0163	0.1788
No.23-CC2	③-1.3 D	Good	39.7278	0.1139	13.0194	0.2255	39.5674	0.1139	13.0187	0.2255
No.24-CC2	①-0.9 F	NG	46.1142	0.0918	9.1891	0.2937	46.1287	0.0918	9.1564	0.2937
No.25-CC2	①-0.9 F	NG	36.1240	0.1030	26.6762	0.1885	35.9754	0.1030	26.6669	0.1885
No.26-CC2	①-0.9 F	NG	38.2786	0.0961	21.9691	0.1837	38.2399	0.0961	21.9642	0.1837
No.27-CC2	①-0.9 F	NG	44.5326	0.0894	13.5703	0.2664	44.5311	0.0894	13.5680	0.2664
No.28-CC2	②-0.9 O	NG	39.0126	0.1132	25.4623	0.1354	38.8641	0.1132	25.1512	0.1354
No.29-CC2	②-0.9 O	NG	40.5342	0.0975	22.4666	0.3042	40.4554	0.0975	22.3539	0.3042
No.30-CC2	①-1.3 F	NG	37.0662	0.1109	25.6351	0.2754	37.0586	0.1109	25.6348	0.2754
No.31-CC2	①-1.3 F	NG	37.3078	0.1069	24.9793	0.2296	37.3073	0.1069	24.9118	0.2297
No.32-CC2	①-1.3 F	NG	34.4628	0.1216	21.0261	0.2673	34.4550	0.1216	21.0249	0.2673
No.33-CC2	①-1.3 F	NG	37.5636	0.1092	22.8136	0.2404	37.5635	0.1092	22.7989	0.2404
No.34-CC2	①-1.3 F	NG	37.7325	0.1109	20.0425	0.2412	37.7277	0.1109	20.0422	0.2412

주) 1. Condition : ①, ②, ③ is crash test method
2. Condition 0.9 and 1.3 is vehicle weight
3. Condition F is head on collision center of facility, O is 1/4 Offset head on collision, D is 15° head on collision

Collision behavior of Crash cushion occurred very short time under 0.4 second. It

is not easy for calculation because it shows complexity behavior of the third dimensions. Therefore main design of the crash cushion is head on collision test. If passenger safety index is no difference only using of x-axis acceleration, it may easily calculate using of X-axis acceleration to apply single degree of freedom.

Figure 4 is comparing error rate, in the calculation of passenger safety using measurement data of x-axis acceleration, y-axis acceleration and yaw angular velocity from vehicle crash test during 34times crash test(All data) and calculation which uses only x-axis acceleration.



<All-Data>
X-axis acceleration = Raw Data
Y-axis acceleration = Raw Data
Yaw angular velocity = Raw Data

<X-Data>
X-axis acceleration = Raw Data
Y-axis acceleration = 0
Yaw angular velocity = 0

Figure 4. Error rate of All-data result and X-Data result

The result which is gap of passenger impact velocity(THIV) is showing that the maximum error rate of THIV is 0.90% and the average error rate is 0.14%, also gap of passenger acceleration (PHD) is maximum error rate is 1.69% and average error rate is 0.26%. There are no time error rates in THIV but PHD has the maximum time error rate 0.58% and the average time error rate 0.03%.

Therefore, hardly affected, and the passenger safety of crash cushion the results were able to confirm even if they applied three-dimensional complicated collision behavior to the single dimensions that used x-axis acceleration data only. This chapter result will use important basis to develop design method of crash cushion for using single degree of freedom.

5. Development of crash cushion's design method using single degree of freedom.

5.1 Crash analysis of crash cushion CC1

There are two ways to evaluate crash cushion CC1 presented in figure 3 showing head-on and side collision. This study doesn't use the side collision, only the data of frontal collision. Because the side clash test possesses the characteristics of scattering or behavior of crash cushion rather than passenger's safety. Therefore, this study is designed only considering the frontal collision. Crash cushion CC1 used in vehicle clash test is using pensile strength of iron bar and compressed air of rubber tire. This product is established on general concrete pavement. The size is 2,380mm(length) × 890mm(width) × 890mm(height).

Table 5 represents result of an actual vehicle crash test by TEST① in table 1. After collision the vehicle did not overturn and stood up straight on the road. Also no elements of crash cushion pierced the inner part of vehicle and there was no scattering of structural part. The result of crash test is satisfied in every item. Crash cushion CC2, CC3 can be designed by use crash test data of crash cushion CC1. Figure 6, 7 are deformation on impact force, impact energy and data of crash test result.

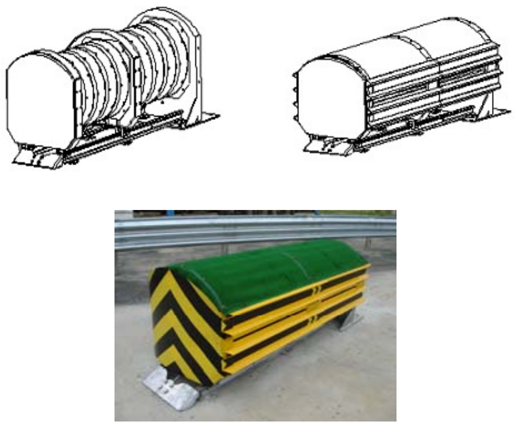


Figure 5. Whole size of crash cushion CC1

Table 5. The result of occupant risk index

Item	Standard	Result
THIV	≤ 44 km/h	38.0 km/h
PHD	≤ 20 g (g = 9.8 m/s^2)	18.5 g

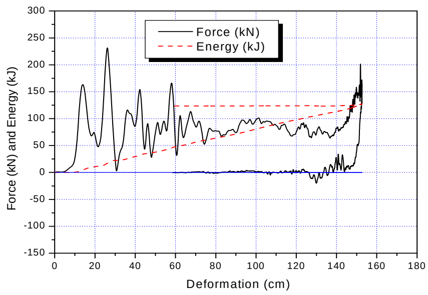


Figure 6. Transformational graph on impulsive power and energy

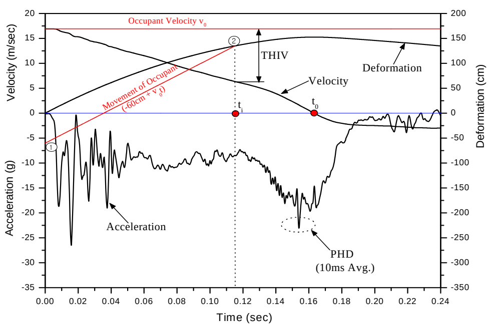


Figure 7. The graph of crash test result

5.2 Design of crash cushion using single freedom of degree

This study suggested design method uses only passenger's x-axis acceleration from the result of crash cushion verified by crash test. Design Method of this study improves confidence and accuracy using data of a vehicle crash test. But there are conditions that should precede a crash test of crash cushion CC1 and structure of crash cushion CC2, 3 is identical to CC1. Still this design is planned based on a vehicle crash test data, and so it can plan the most suitable length of product considering valid deformation distance on crash cushion CC2, 3. Therefore designed crash cushion CC2, CC3 by single degree of freedom are identical with CC1, except the length of crash cushion. It is not difficult to know the structural characteristic of crash cushion as showing graph relationship between resisting force and displacement during collision. Figure 8 is a curve of x-axis acceleration and displacement measured after collision on crash cushion CC1.

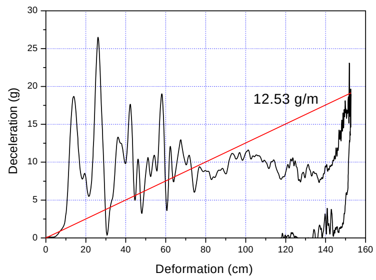


Figure 8. Acceleration-displacement by time record

An approximate value of triangular incline that has same area with integrated acceleration area before it generates elastic return can be fined 12.53g/m regardless of velocity. It represents spring constant unit mass, k/M .

If collision of vehicle and crash cushion sees in single degree of freedom using M , mass of collision vehicle and spring constant k , what a/x is regular regardless of velocity means k/M is regular.

Suppose that characteristic of crash cushion(system stiffness) is regular, the natural frequency, ω^2 , of single degree of freedom is regular regardless of collision velocity. The second chapter explained that if it uses single degree of freedom, displacement and acceleration of collision vehicle-crash cushion the values could be

found. That is to say that movement equation can be written formula 5, displacement, velocity and acceleration can be written formula 6, 7, 8 respectively and this formula sees that v_0 is velocity of initial collision, ω is $\sqrt{k/M}$ which means natural frequency of single degree of freedom. Also the maximum displacement and acceleration can be seen formula 9, 10 as a function of initial velocity, v_0.

As already mentioned, if the stiffness of crash cushion is decided, the value k/M does not change according to collision speed. Therefore ω =($\sqrt{k/M}$) is 11.087 $radians/\sec$ regardless of collision velocity. Also acceleration ($\ddot{x}$) has the maximum value $v_0\omega$ at $\omega t = \pi/2$, so t_{max} = 0.1sec, that time the maximum acceleration is seen formula 11.

$$
\begin{aligned}
|\ddot{x}_{max}| &= v_0\omega \\
&= 11.087 rad/\sec \times v_0 km/hr \times 0.278 m/\sec/km/hr \\
&= 3.079 v_0 m/\sec^2 = 0.314 v_0 (g)
\end{aligned}
\tag{11}
$$

In here, a unit of v_0 is km/hr and a unit of the maximum acceleration is gravitational acceleration(g), crash cushion ω^2 =12.53g/m from formula 10, so the maximum displacement is the same with formula 12.

$$
\begin{aligned}
x_{max} &= v_0/\omega \\
&= \sqrt{1/(12.53 \times 9.81)} \sec/rad \times v_0 km/hr \\
&\times 27.78 cm/\sec/km/hr = 2.505 v_0
\end{aligned}
\tag{12}
$$

In formula 12, a unit of x_{max} is cm and v_0 is km/hr. Formula 11, 12 confirm that when the vehicle collide with crash cushion, if spring constant k can be found, single degree of freedom' ω regardless of collision velocity is found and the maximum acceleration and displacement is calculated by formula 9, 10.

The result of crash test about crash cushion CC1 is applied to the design of single degree of freedom that is developed by this study. Using these formula, table 6 shows the maximum acceleration and valid deformation distance of crash cushion CC2 (collision velocity 80km/h) and CC3 (100km/h).

Table 6. The maximum acceleration and valid deformation distance of CC2, CC3

Division	CC2	CC3
the maximum acceleration(g)	25.12	31.4
the maximum distance(cm)	200.4	250.5

5.3 Verification of crash cushion design method using single degree of freedom

A vehicle crash test is performed by Korean guide. In here, crash cushion CC2 is the object of this test. Crash cushion CC2 is identical with crash cushion CC1 in all condition such as width, height and structure, but the length of product is different. Crash cushion CC2's length is total 4,330mm(including itself 2.8m); it applied to the maximum valid deformation distance. The length of crash cushion must be decided after consideration including the maximum valid deformation distance(2.0m), structural characteristic and thickness of crash cushion. The result of crash test about crash cushion CC2 applied to single degree of freedom has satisfied outcomes for every item. Table 7 shows the result of crash test performed by a guide.

Effectiveness of single degree of freedom for crash cushion CC2 passes 6 times crash test by a guide and finally gets a satisfied result.

Figure 9. Crash cushion CC2

Table 7. The result of crash cushion CC2 crash test

condition	Evaluation item		
	(THIV)	(PHD)	Behavior of crash cushion and vehicle
head on collision 1.3ton vehicle	40.5 km/h	11.6 g	No scattering of element part **good**
head on collision 0.9ton vehicle	43.8 km/h	13.0 g	No element part of separation **good**
head on collision (1/4 of vehicle's width)	43.2 km/h	15.3 g	stands up on the road after test **good**
head on collision 15°	39.7 km/h	13.0 g	No deformation of the vehicle's inside **good**
broad side collision 15°	18.5 km/h	7.7 g	**good**
broad side collision 165°	27.2 km/h	4.9 g	**good**

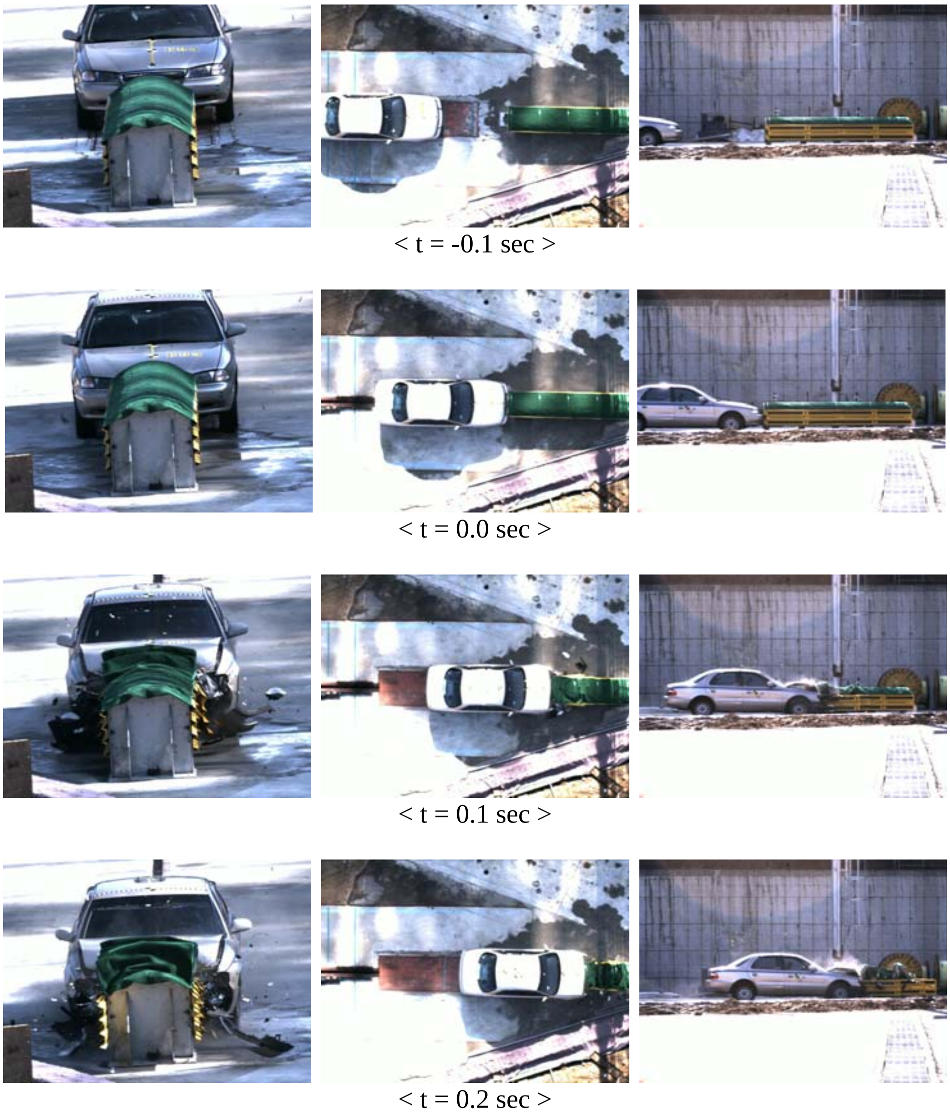


Figure 10. Crash test of crash cushion CC2

6. Conclusion

Crash cushion CC1 can be verified through two times crash test according to Korea evaluation guide, but CC2 and CC3 should be done with six times crash test. CC1's successful ratio is relatively high while CC2 and CC3 is low. Also crash cushion CC1 is easy to be developed, but CC2 and CC3 is difficult. This study suggested the design method of single degree of freedom crash cushion, so that it can develop CC2 and CC3 to be rapid and inexpensive using crash cushion CC1.

The results of producing crash cushion CC2 and executing performance through a vehicle crash test is very satisfied. Judging from this, the design method of single degree of freedom is proved one of the best ways to design crash cushion. The researchers are planning to improve the single degree of freedom crash cushion more practically through performing crash test on crash cushion CC3.

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